Geological Society of Malaysia, Bulletin 53, June 2007, pp. 111 – 117

New trace, major and rare earth element data for the Early Pleistocene alkali olivine basalts and olivine nephelinites from Kuantan, Pahang: Plume-related rift volcanics or wrench-related crustal extension?

AZMAN A. GHANI AND NUR ISKANDAR TAIB

Department of Geology University of Malaya
50603 Kuala Lumpur, Malaysia

Abstract: The Kuantan Basalts are one of the very few bodies of basic extrusives in Peninsular Malaysia. It was erupted too late to have been caused by the Albian rifting that formed the sedimentary basins off the Peninsula's East Coast, the mid-Oligocene extension caused by the collision of the Indian subcontinent and Asia, or by the compression beginning in the mid-Miocene that followed it. This paper presents new trace element data for alkali olivine basalts and olivine nephelinites belonging to the Kuantan Basalt. Both are enriched in incompatible and light rare earth elements, with signatures comparable to Oceanic Island Basalts and East African Rift basaltoids. They plot in the Intraplate Basalt field on a Zr-Ti-Y discrimination plot. The geochemical evidence, as well as the timing, points to a mantle plume-related genesis, rather than one related to wrench tectonics-induced extension.

INTRODUCTION

The 1.6 Ma (Bignell and Snelling, 1977) Kuantan Basalt represents one of the largest bodies of basic extrusives in Peninsular Malaysia, located to the north of the port city of Kuantan on the Peninsula's east coast (Figure 1). Variously described as olivine basalt both with and without nepheline (Fitch, 1952), olivine basalt and basanite (Abdul Hanif, 1975), and as olivine basalt, limburgite and olivine nephelinite (Chakraborty, 1977), with olivine basalt being dominant towards the west, and olivine nephelinite to the east. Limburgite (an extrusive rock containing olivine and augite, with little, if any, feldspar or nepheline) is negligible in volume at the current level of exposure. Fresh exposures are rare, but includes the famous "Pantai Batu Hitam" (Black Rock Beach) just north of Kuantan. The extent of the basalt can be mapped using the deep red soil it produces. It was erupted on top of Permian-Triassic granites to the east, and upper Paleozoic sediments to the west (see Figure 1). The alkali

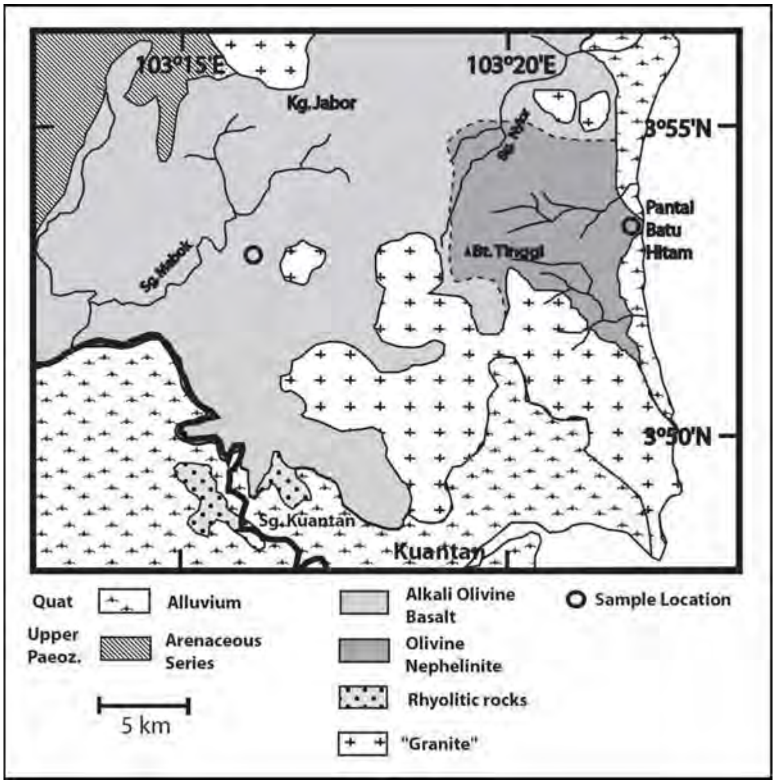

Figure 1: Geologic map of the Kuantan area, showing the extent of the Kuantan Basalt.

olivine basalt ranges compositionally from alkali olivine basalt to hawaiite, and are nephline to hypersthene normative. Chakraborty (1980) showed that the olivine nephelinite was not a differentiate of the alkali olivine basalt.

This paper will report new major and trace element data obtained from three samples each of olivine nephelinite (collected at Pantai Batu Hitam) and alkali olivine basalt (collected at Jabor, near the Kuantan bypass, Figure 1).

PETROGRAPHY

The alkali olivine basalts in this area were extensively described by Fitch (1952) and Abdul Hanif (1975), while the olivine nephelinites were described by Chakraborty (1977). In brief, the alkali olivine basalt is a grey rock containing visible green olivine and black pyroxene phenocrysts. It is locally porphyritic, and flow structures can sometimes be observed (Abdul Hanif, 1975). The olivine nephelinites are *"fine-grained, aphyric to microphyric, containing microphenocrysts of olivine and clinopyroxene set in a holocrystalline groundmass dominated by tiny prisms of clinopyroxene and euhedral to subhedral grains of nepheline"* (Chakraborty, 1977).

GEOCHEMISTRY

The major, trace and rare earth element data presented here was obtained by XRF at the National Research Center of Geoanalysis of China. Table 1 contains major and trace element data, as well as CIPW norms. Table 2 contains REE data for one (unrelated) sample of alkali olivine basalt.

The olivine nephelinites (KTN1-KTN3) contain less silica (40.8%) than the alkali olivine basalts (KTN4-KTN6, 45.9-52.5%). The olivine nephelinites are highly nepheline normative, while two of the alkali olivine basalts are quartz normative. The three nephelinite samples show remarkably similar values, indicating that the three samples were part of the same eruption, or lava flow.

Zr, Ti and Y data are presented in a discrimination plot (after Pearce and Cann, 1973) in Figures 2a and 2b. REE data is presented in Figure 3, and an incompatible element "Spider Plot" is presented in Figure 4a.

TECTONIC SETTING

The Eastern Belt of the Malay Peninsula and the areas immediately offshore have been subjected to episodes of crustal extension and compression for the last 110 million years. The initial extension was caused by a mantle plume located approximately 150 km from the present shoreline, forming the 1000km wide Malay Dome (Tjia, 1999; see Figure 7.16), the extent of which encompassed the entire Malay Peninsula and the southern peninsula of Vietnam. The Malay, Penyu and West Natuna basins developed as rifts on the flanks of the Malay Dome, with the peak of the dome represented by the present day triple junction between the three basins. The onset of the extension was 110 Ma (Albian, mid-Cretaceous), the age of the oldest of the pervasive dolerite dikes present in granites of the Eastern Belt (Haile *et al*., 1983). Even today, the area surrounding the triple junction is known for its relatively high heat flow.

A second episode of extension was caused by the "hard collision" of the Indian Subcontinent with Asia, at 40 Ma, and its associated extrusion tectonics (Tapponnier *et al*., 1982). Major strike slip faults developed to facilitate the extrusion of South East Asian lithosphere to the east and south, resulting wrench faulting, pull-apart structures (mainly in the Straits of Malacca), and further extension and subsidence in the Malay and Penyu basins. This second episode of extension ended at approximately 25 Ma (late Oligocene). The region then came under compression in the mid Miocene (14 Ma), resulting in the reactivation and reversal in direction of strike-slip faults, thrust faulting and folding, and inversion tectonics within the Malay and Penyu basins. The peak of the compression took place between 12.5 and 11 Ma (Mazlan Madon *et al*., 1999).

The extent of rift related alkaline basalt magmatism in South East Asia is summarized in Hutchison (1996; Section 8.8). A major occurrence, of alkali basalts is in south eastern Indochina, the main occurrences being to the north and west of Ho Chi Minh City, but extending west to Phnom Penh and to the north to the Bolovens Plateau (see Hutchison, 1996; Figure 3.3). They range in age from the Miocene to the Present (Nguyen, 1982). More than two decades of exploration has not revealed occurences of basalt in the Malay Basin, however they have been encountered in the Penyu Basin (Wong, *et al*. 2006), and on Midai, a small island to the south west of Natuna (Van Bemmelen, 1970).

DISCUSSION

The Kuantan Basalt occupies an enigmatic place in the geology of the region. Its location would suggest a relationship to the rift basins offshore; in fact, before the determination of their ages, it was suggested that the dolerite dikes fed the eruption of the Kuantan Basalt. However, the great disparity between their ages precludes that (Haile, *et al*., 1983). Dated at 1.6 Ma (early Pleistocene), the Kuantan Basalt is too young to be related to the dolerite dikes in the Eastern Belt and the initial onset of rifting caused by the Malay Dome mantle plume, and also too young to have been caused by the transtensional extension caused by the India-Asia collision. It is also too young to have been erupted due to the compression and inversion in the Miocene.

Generally, alkali-rich basaltic magmas are produced during continental rifting, during the early phases of oceanic island magmatism, and less commonly, during

Table 1: Major (wt%) and trace element (ppm) contents and CIPW norms (%) for olivine nephelinite and alkali olivine basalt samples.

	KTN1 Olivine Nephelinite	**KTN2** Olivine Nephelinite	**KTN3** Olivine Nephelinite	**KTN4** Alkali Olivine Basalt	**KTN5** Alkali Olivine Basalt	**KTN6** Alkali Olivine Basalt
SiO_2	40.84	40.78	40.83	45.94	52.43	52.52
TiO_2	2.41	2.43	2.43	1.85	1.74	1.77
Al_2O_3	12.09	12.11	12.07	13.42	14.42	14.47
FeO*	12.77	12.70	13.04	10.85	9.67	9.46
MnO	0.21	0.20	0.22	0.18	0.14	0.14
MgO	9.43	9.09	9.37	9.33	6.99	6.73
CaO	11.16	11.26	11.00	9.78	7.40	7.41
Na_2O	4.54	4.18	4.33	2.95	3.59	3.56
K_2O	2.14	1.87	1.99	2.02	1.32	1.15
P_2O_5	1.03	1.04	0.99	0.81	0.30	0.30
Total*	96.62	95.67	96.27	97.13	97.99	97.51
Mg Number	0.57	0.56	0.56	0.61	0.56	0.56
CaO/Al_2O_3	0.92	0.93	0.91	0.73	0.51	0.51
Al_2O_3/TiO_2	5.01	4.98	4.97	7.25	8.29	8.18
CaO/Na_2O	2.46	2.69	2.54	3.32	2.06	2.08
***Totals presented without LOI**						
CIPW norms						
Quartz	0	0	0	0	1.14	2.38
Plagioclase	4.98	8.76	7.62	34.37	49.71	50.23
Orthoclase	0.03	10.17	8.28	11.94	7.80	6.80
Nepheline	20.81	19.16	19.85	4.33	0	0
Leucite	11.94	0.69	2.73	0	0	0
Diopside	35.13	32.45	32.60	20.72	12.42	11.84
Hypersthene	0	0	0	0	18.59	17.95
Olivine	11.46	11.69	12.42	15.50	0	0
Ilmenite	4.58	4.62	4.62	3.51	3.30	3.36
Magnetite	6.18	6.13	6.31	5.25	4.67	4.57
Apatite	2.39	2.41	2.29	1.88	0.70	0.70
Total	97.5	96.08	96.72	97.50	98.33	97.83
Trace Elements						
Ni	145	148	143	237	721	321
Cr	170	162	177	322	241	223
Sc	16	15	14	17	16	18
V	174	177	172	162	150	152
Ba	685	631	557	402	214	194
Rb	24	22	22	32	22	19
Sr	1365	1388	1418	903	378	389
Zr	300	309	311	221	111	110
Y	31	31	30	24	20	22
Nb	126	130	131	78	22	22
Ga	23	23	22	20	20	19
Cu	61	63	66	79	104	96
Zn	137	143	139	115	158	124
Pb	53	5	5	3	4	2
La	71	74	77	49	13	18
Ce	130	129	133	75	29	29
Th	11	11	10	7	2	2
Nd	63	62	62	35	16	18

Table 2: REE contents in ppm for olivine alkali basalt (1 sample, unrelated to samples in Table 1).

La 18.1	**Ce** 32.7	**Pr** 4.69	**Nd** 18.6	**Sm** 4.9
Eu 1.75	**Gd** 4.67	**Tb** 0.74	**Dy** 4.05	**Ho** 0.77
Er 1.85	**Tm** 0.28	**Tb** 1.75	**Lu** 0.29	**Y** 20.1

Table 3: Trace and rare earth element concentrations (in ppm) for E-Morb, from Sun and McDonough (1989). Values used for normalization.

REE:				
La 6.30	**Ce** 15.0	**Pr** 2.05	**Nd** 9.0	**Sm** 2.60
Eu 0.91	**Gd** 2.97		**Dy** 3.55	**Ho** 0.79
Er 2.31		**Yb** 2.37	**Lu** 0.35	
Trace elements:				
Cs 0.06	**Rb** 5.0	**Th** 0.60	**U** 0.18	**K** 2092
Nb 8.30	**Ta** 0.47	**Sr** 155	**P** 624	**Zr** 73
Hf 2.03	**Ti** 6005	**Y** 22.0		

back arc spreading. Competing explanations for the eruption of the Kuantan basalt include incipient continental rifting (related to a mantle plume, resulting in a triple junction rift); "oceanic island" type magmatism (also caused by a mantle plume, but erupted over oceanic crust) – if this were to take place at Kuantan, the plume would have to have injected magma through a weak zone in the overlying lithosphere without causing rifting); localized crustal extension caused by wrench or inversion tectonics without the involvement of a mantle plume; or the presence of an ancient block of alkali basalt in the lower crust, the result of earlier rifting or even backarc spreading, that has become remelted or remobilized.

The Zr-Ti-Y discrimination plot (Figure 2a, after Piece and Cann, 1973) puts both the Olivine Nephelinites and the alkali olivine basalts in the "Intra-plate Basalt" field. N-MORB, E-MORB, Oceanic Island Basalt (Sun and McDonough, 1989) and backarc alkali basalts from the Marianas Trough (Bloomer, 1983) are also plotted, for comparison.

Figure 2b superimposes 618 analyses for basalts, alkaline basalts, alkali olivine basalts, basanites and nephelinites from numerous studies (see the figure caption for references) from the East African Rift. Note that while the Zr-Ti-Y diagram is not supposed to apply to alkali basalts, with a few exceptions, they all plot within the Intraplate Basalt field. The high Y, high Ti alkali basalt outliers are from the Southern Kenya Rift (LeRoex *et al.*, 2001).

Figure 3 shows REE abundances normalized to E-MORB (normalization values from Sun and McDonough, 1989, presented in Table 1). The data presented here is from Chakraborty *et al.* (1980), with the addition of one new alkali olivine basalt analysis. For comparison, N-MORB and OIB composite analyses (from Sun and McDonough, 1989), and one back arc basalt from the Marianas Trough (Volpe *et al.*, 1987) are also plotted for comparison. (E-MORB, of course, plots at a normalized abundace of unity, across the board.) While both olivine nephelinites and alkali olivine basalts show the strong enrichment in LREEs reminiscent of OIB, the olivine nephelinites show a much stronger enrichment. By contrast, the back arc basalt resembles E-MORB in REE abundance.

Figure 4a is a incompatible element "spider" plot, with elements arranged in oder of increasing compatibility, and values normalized to E-MORB. As with the REE plot, the olivine nephelinite shows a greater enrichment towards the left side of the chart compared with the alkali olivine basalt, which is also enriched with respect to E-MORB. Both show patterns similar to OIB. By contrast, N-MORB is highly depleted on the left side, while another back-arc sample (from tbe Bransfield Strait, from Weaver *et al.*, 1979) plots close to E-Morb (that is, close to unity).

Figure 4b is to the same Y axis scale as Figure 4a, and on it are plotted composite lines representing 81 basalts (4 studies), 51 alkali basalts (3 studies), 36 alkali olivine basalts (3 studies) and 11 nephelinites (3 studies) from the East African Rift. The great similarity between East African Rift basaltoids and OIB is clear, with the nephelinites showing the most enrichment overall.

CONCLUDING REMARKS

We should be able to discount any hypothesis that involves the remelting of an earlier basalt, since basalts (and their phaneritic counterparts) are mantle derived partial melts with very high melting points. A low temperature, hydrous partial melt of a basalt would be much more silicic. Based on trace element and REE distributions alone, we can, at this time, also discount a backarc origin (direct, latent, relict or otherwise). Likewise, these basalts are very unlike those found at oceanic spreading centers, or those related to volcanic arcs. The Kuantan basaltoids resemble Oceanic Island Basalts as well as East African Rift basaltoids.

Trace element discrimination diagrams, rare earth element plots and incompatible element plots are extensively used in the study of basalts, the differences between plate tectonic setting giving rise to different signatures. They do, however, have their limitations – continental rifting gives very similar trace element signatures compared to oceanic island environments (Gunn, 2007), not perhaps too surprising, since both involve mantle plumes and deep (90 km) partial melting of mantle (Figures 2b and 4b). However, since it is firmly established that the Kuantan Basalts lie atop continental crust, the distinction is, in this case, moot.

More relevant to the discussion is whether these rocks could have been erupted as a result of wrench/inversion tectonics, a sort of incipient pull-apart volcanism, without the involvement of a mantle plume (hot spot). Large mantle plumes, during the time of their activity, give rise to a doming of the overlying lithosphere. If the plume were a small one, it might not leave any such sign, but in

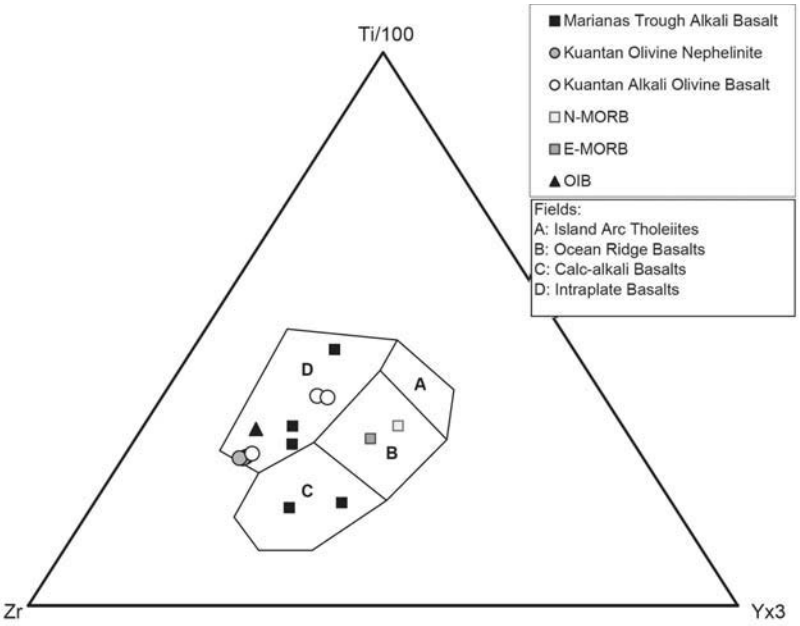

Figure 2a: Ti-Zr-Y discrimination diagram, after Pearce and Cann, 1973. Fields are: A – island arc tholeiites. B – MORB, island arc tholeiites and calc-alkali basalts. C – calc-alkali basalts. D – intra-plate basalts. N-MORB, E-MORB and OIB values are those given in Sun and McDonough (1989) and compiled in Floyd (1991).

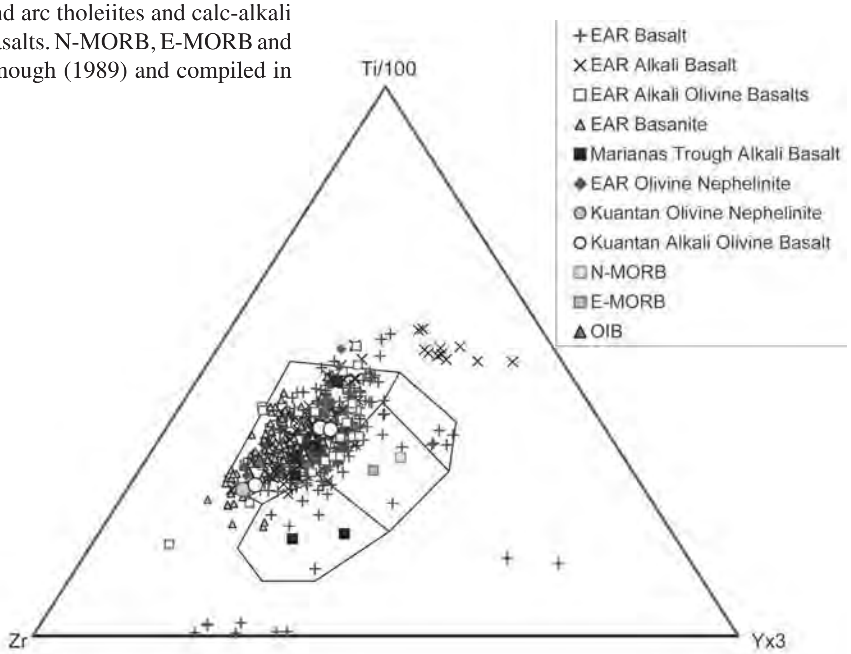

Figure 2b: Ti-Zr-Y discrimination diagram, showing data from the East African Rift. Studies from which the data are taken are too numerous to include in the list of references, so are mentioned here in brief, together with their GEOROC reference numbers (in square brackets) and the number of data points. A complete listing is available from the author on request. Basalts: [2823] Stewart K.(1996) 14 Data Points; [2852] Deniel C.(1994), 45; [7671] Furman T.(1999) 1, [7690] Barrat J. A.(2003), 14; [7720] Kabeto K.(2001), 12; [7729] Rogers N. W. (2000), 3; [7783] Paslick C. R.(1995), 5; [7814] Black S.(1998), 6; [7885] Peccerillo A.(2003), 5; [7928] Haileab B.(2004), 10; [8029] Macdonald R.(2001), 6; [8060] Davies G. R.(1987), 12; [8094] Baker B. H.(1977), 10; [8101] Gasparon M.(1993), 31; [8104] Bloomer S. H.(1989), 14; [8110] Yemane T.(1999), 6; [8111] Barberio M. R.(1999), 32; [8314] Barrat J. A.(1998), 21; [8582] Chernet T.(1999), 5; [8583] Boccaletti M.(1995), 28 ; [8669] Rooney T. O.(2005), 18 ; [9198] Furman T.(2006), 41 ; [9311] Weaver S. D.(1977), 3 ; [9672] Rogers N. W.(2006), 13 ; [9692] Ayalew D.(2006), 5 ; [9700] Lowenstern J. B.(2006), 3 ; [9726] Ren Minghua(2006), 4 . Alkali basalts: [7625] Trua T.(1999), 2; [7751] Le Roex A. P.(2001), 12; [7806] Furman T.(1995), 11; [8068] Class C.(1994), 12; [8084] Späth A.(2001), 4; [8110] Yemane T.(1999), 17; [8179] Marcelot G.(1989), 7; [8187] Tatsumi Y.(1991), 21; [8202] Sceal J. S. C.(1971), 3; [8910] Clément J.-P.(2003), 6; [9528] Wolde B.(1994), 5. Alkali olivine basalts: [7729] Rogers N. W.(2000), 21; [8029] Macdonald R.(2001), 11; [9403] Brown F. H.(1971), 4. Basanites: [7720] Kabeto K.(2001), 1; [7729] Rogers N. W.(2000), 6; [7751] Le Roex A. P.(2001), 2; [7783] Paslick C. R.(1995), 9; [7806] Furman T.(1995), 7; [7817] Paslick C. R.(1996), 5; [8029] Macdonald R.(2001), 9; [8063] Rogers N. W.(1992), 13; [8068] Class C.(1994), 24; [8084] Späth A.(2001), 10; [8110] Yemane T.(1999), 1; [8179] Marcelot G.(1989), 10; [9402] Brown F. H.(1969), 5; [9323] De Mulder M.(1985), 2; [9373] Freerk-Parpatt M.(1990), 1; [8605] Aoki K.-I.(1985), 3. Olivine nephelinites: [8179] Marcelot G.(1989), 2; [8062] Simonetti A.(1994), 5.

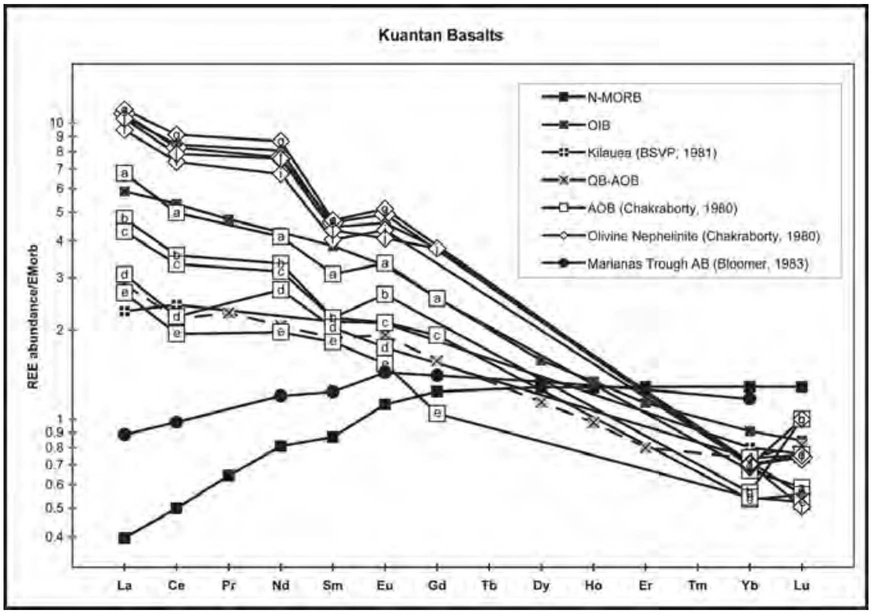

Figure 3: REE abundances normalized to E-Morb (EMorb values from Sun and McDonough, 1989). Kuantan Basalt data is from Chakraborty et.al, 1980, except QB-AOB (alkali olivine basalt, new data). Data from Chakraborty *et al.* (1980): Alkali olivine basalts: QB-12=a, QB-2=b, QB-46B=c, QB-36=d, QB-13=e. Olivine nephelinites: QB-38=f, QB-22=g, QB-8=h, QB-15=i, QB-49C=j.

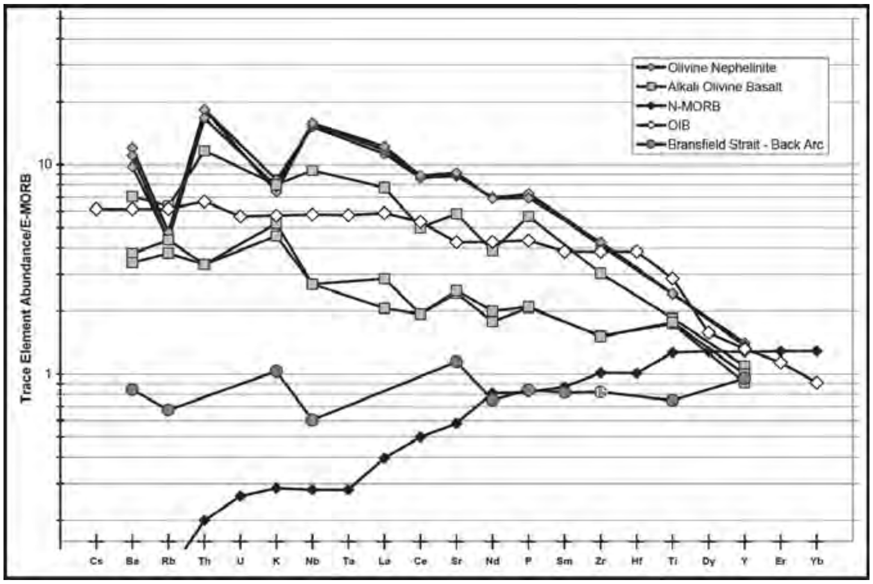

Figure 4a: Incompatible element "spider" plot, showing incompatible element abundances normalized to E-MORB, with the elements arranged in order of decreasing incompatibility. N-MORB, E-MORB, OIB values are from Sun and McDonough (1989). Bransfield Strait (back-arc basalt) – from Weaver *et al.* (1979).

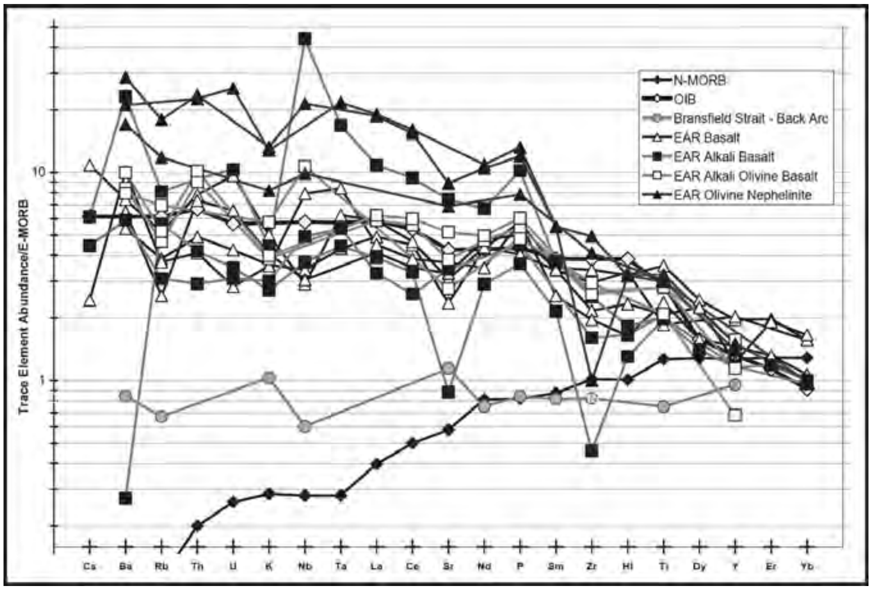

Figure 4b: Data from East African Rift basaltoids. Studies are not listed in the bibliography – citations are available upon request, and are listed here with their GEOROC reference numbers, and the number of analyses in the composite sample. Basalts: [7928] Haileab B.(2004), 10; [8111] Barberio M. R.(1999), 32; [8583] Boccaletti M.(1995), 27; [9672] Rogers N. W.(2006), 12. Alkali basalts: [2929] Brotzu P.(1980), 22; [7751] Le Roex A. P.(2001), 11; [7806] Furman T.(1995), 17. Alkali olivine basalts: [7729] Rogers N. W.(2000), 21; [8029] Macdonald R.(2001). 11; [9403] Brown F. H.(1971), 4. Olivine nephelinites: [8179] Marcelot G.(1989), 3; [8584] Hertogen J.(1985), 3; [8062] Simonetti A.(1994), 5.

any case, there is no physical evidence for a plume in Recent times under Kuantan.

There is also the question as to whether plumeless extensional volcanism can generate similar geochemical signatures to those found in plume-related settings. Comparison with early erupted basalts of pull-apart basins might prove useful, but most of these develop in oceanic crust. It would also be useful to have the age of the rocks confirmed, perhaps by the Ar-Ar method. Given the timing, it is unlikely that the Kuantan Basalt was caused by any sort of wrench-related extension, though eruption after the fact, through existing wrench-related weak zones or fractures, is still plausible. The GEOROC database (GEOROC, 2007) is a very good tool for the comparative geochemistry of basalts, and will be of great use here. A more plausible explanation, given the strong OIB/Rift Valley geochemical signature, is that the Kuantan Basalt is a product of continuing activity of the same mantle plume that produced the Malay Dome and the Malay and Penyu basins, the magmas finding their way to the surface through an existing weak zone or fracture system.

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Paper Code NGC07/40
Manuscript received April 2007
Revised manuscript received 28 May 2007